LIQUID FLOW SENSOR FOR X-RAY TUBES

The present application relates to the x-ray tube arts. The invention finds particular application in monitoring the flow of a cooling liquid to an x-ray tube and will be described with particular reference thereto. It will be
5   appreciated, however, that the invention finds application in a variety of fluid systems where it is desirable to monitor fluid flow or thermal characteristics.

x-ray tubes typically include an evacuated envelope made of metal, ceramic, or glass which is supported within an
10   x-ray tube housing. The envelope houses a cathode assembly and an anode assembly. The cathode assembly includes a cathode filament through which a heating current is passed. This current heats the filament sufficiently that a cloud of electrons is emitted, i.e. thermionic emission occurs. A high
15   potential, on the order of 100-200 kV, is applied between the cathode assembly and the anode assembly. The electron beam strikes the target with sufficient energy that x-rays are generated, along with large amounts of heat.

An x-ray tube housing surrounding the tube defines a
20   flow path for a coolant fluid, such as oil, to aid in cooling components housed within the envelope. In order to distribute the thermal loading created during the production of x-rays, a constant flow of cooling liquid is maintained throughout x-ray generation. After circulating through the x-ray tube housing,
25   the cooling liquid is passed through a heat exchanger. The optimum flow rate of cooling liquid depends on a number of factors, including the x-ray tube power, its duty cycle, and the effectiveness of the cooling system. In the event that the liquid flow rate drops below a minimum level, for example, due
30   to pump malfunction, overheating of the x-ray tube components tends to occur, which is detrimental to the lifetime of the tube.

Various systems have been developed to monitor liquid flow in an x-ray tube cooling system. In one system, a flow

switch is positioned in the path of the fluid flow. As the liquid flows through the switch, the liquid displaces a magnet, which in turn actuates a hermetically sealed reed switch. A positive spring return deactivates the switch when the flow
5   decreases. A flow indicator, such as a paddle wheel, is often used together with the flow switch to provide a visual flow indicator. The liquid passing the flow indicator spins the wheel, visually indicating flow speed.

Because both the flow switch and flow indicator are
10   installed in line with the liquid flow, their presence inevitably creates flow resistance which reduces the liquid flow rate. This reduces the cooling capacity of the cooling system.

In an alternative system, a pressure switch is used
15   to monitor the liquid flow indirectly. The pressure switch is usually installed at the outlet of the pump used to circulate the cooling fluid. If the detected pressure decreases below a preselected level, the pressure switch automatically shuts down the x-ray tube. A sharp drop in pump pressure is often an
20   indicator that the pump is losing power or failing.

In the case of the pressure switch, however, pump outlet pressure does not always accurately predict flow rates. For example where flow lines of the cooling system become partially obstructed or twisted, the pump pressure tends to
25   increase as the pump works harder to maintain flow through the obstruction. As the pump starts to fail, the pressure "drops" to normal, but the flow, due to the obstruction, is below normal. Thus, the pressure switch does not always protect the x-ray tube from overheating due to the loss in liquid flow.
30   The temperature of the cooling fluid within the x-ray tube housing depends not only on the flow rate, but also on other factors, such as the duty cycle power. An algorithm computes the maximum power which can be used in a subsequent scanning operation, based on the duty cycle, the tube heat
35   storage, and a predicted temperature in the cooling liquid. Over time, the accuracy of the algorithm computations decreases due to increasing differences between the actual and the

predicted temperatures and cooling rates. To compensate for these inaccuracies, the x-ray tube is often removed from service for an extended period during the day, such as an hour or more at mid day, to allow the x-ray tube to cool to a know

5   set point.

The present invention provides a new and improved method and apparatus which overcome the above-referenced problems and others.

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In accordance with one aspect of the present invention, an assembly is proved. The assembly includes an x-ray tube. The x-ray tube includes an envelope which defines an evacuated chamber in which x-rays are generated. A housing

15   surrounds at least a portion of the envelope. A cooling system circulates a cooling liquid through the housing to remove heat from the x-ray tube. The cooling system includes a pump and a flow sensor system which is responsive to a pressure difference across the pump.

20   In accordance with another aspect of the invention, a method for controlling operation of an x-ray tube is provided. The method includes circulating a cooling fluid through a housing and over the x-ray tube with a pump. Heat is removed from the cooling fluid which has circulated through the

25   housing. A flow rate of the cooling fluid is determined. This step includes determining a pressure difference across the pump or a function which correlates with the pressure difference and determining the flow rate from the pressure difference or function.

30   In accordance with another aspect of the invention, a system for removing heat from an associated x-ray tube assembly is provided. The system includes a fluid flow path which carries a cooling fluid to at least a portion of the associated x-ray tube, and removes heat therefrom. A pump circulates the

35   cooling fluid through the fluid flow path. Means are provided for determining a pressure difference across the pump. Means

responsive to the determined pressure difference are provided for controlling operation of the x-ray tube.

One advantage of at least one embodiment of the present invention is that it enables flow rates in an x-ray tube cooling system to be determined.

Another advantage of at least one embodiment of the present invention is that it enables flow rates to be determined without reducing the liquid flow.

Another advantage of at least one embodiment of the present invention is that x-ray tube down time is reduced due to a more accurate prediction of x-ray tube power capabilities.

Another advantage resides in extending x-ray tube life.

Still further advantages of the present invention will become apparent to those of ordinary skill in the art upon reading and understanding the following detailed description of the preferred embodiments.

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of illustrating a preferred embodiment and are not to be construed as limiting the invention.

FIGURE 1 is a diagrammatic illustration of an x-ray tube and cooling system according to a first embodiment of the present invention;

FIGURE 2 is a more detailed diagram of the x-ray tube and cooling system of FIGURE 1;

FIGURE 3 is a schematic view of the pressure sensing system of FIGURE 2;

FIGURE 4 is an exemplary plot of liquid flow rate in gallon/minute (GPM) vs. the differential pressure across a pump in Bar;

FIGURE 5 is an exemplary plot of the differential pressure across a pump (Bar) vs. transducer output in millivolts (mV);

FIGURE 6 is an exemplary plot of liquid flow rate (GPM) vs. transducer output obtained from the plots of FIGURES 4 and 5;

FIGURE 7 is a diagrammatic view of an x-ray tube and
5   cooling system according to a second embodiment of the present invention; and

FIGURE 8 is a perspective view of a CT scanner incorporating an x-ray tube and cooling system according to the present invention.
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With reference to **FIGURE 1**, a schematic view of a rotating anode x-ray tube **1** of the type used in medical diagnostic systems, such as computed tomography (CT) scanners,
15   for providing a beam of x-ray radiation is shown. The tube includes an anode assembly **10,** which is rotatably mounted in an evacuated chamber **12**, defined by an envelope or frame **14,** typically formed from glass, ceramic, or metal. The x-ray tube anode assembly **10** is mounted for rotation about an axis via a
20   bearing assembly shown generally at **16**. A heated element cathode assembly **18** supplies and focuses an electron beam **A**. The cathode is biased, relative to the anode, such that the electron beam is accelerated to the anode and strikes a target area **20** of the anode. The beam striking the target area is
25   converted in part to heat and in part to x-rays **B,** which are emitted from the x-ray tube through a window **22** in the envelope. The anode is rotated at high speed during operation of the tube. It is to be appreciated that the invention is also applicable to stationary anode x-ray tubes, rotating
30   cathode tubes, and other electrode vacuum tubes.

A housing **30** filled with a heat transfer and electrically insulating cooling fluid, such as a dielectric oil, surrounds the envelope **14**. The cooling fluid is directed to flow past the insert that includes the window **22**, the
35   bearing assembly **16**, cathode assembly **18**, and other heat-dissipating components of the x-ray tube. The cooling fluid is cooled by a cooling system **32**, which receives heated cooling

liquid from the housing through an outlet line **34** and returns cooled cooling liquid via a return line **36**. The lines **34, 36** may be in the form of flexible hoses, metal tubes, or the like.

5   In the illustrated embodiment, the housing **30** is shown as a unitary structure defining an interior cooling space **38** which cools the entire x-ray tube **1**. However, it will be appreciated that the housing may include different regions, which are associated with different portions of the x-ray tube, to allow separate or focused cooling of components which are

10 more prone to overheating. Indeed, the housing may constitute multiple cooling housings, which may be interconnected by fluid lines, or separately connected with the cooling system. Additionally, it is also contemplated that there may be more than one outlet and/or return line to the housing.

15 With reference now to **FIGURE 2**, the cooling system **32** includes a liquid pump **40**, having an inlet **42**, through which cooling fluid enters a chamber **44** of the pump, and an outlet **46**, through which cooling fluid leaves the pump chamber **44**. A heat exchanger **48** removes heat from the cooling liquid prior to

20 return of cooling liquid to the housing. In the illustrated cooling system **32**, heated liquid flows along a fluid flow path **33** via the outlet line **34** to the liquid pump, then by an intermediate fluid line **50** from the pump **40** to the heat exchanger **48**, and finally returning to the housing via the

25 return line **36**. Within the housing **30**, the cooled cooling liquid circulates around the x-ray tube **1**, or components thereof, removing heat before exiting from the outlet line **34**. However, it will be appreciated that the positions of the pump and the heat exchanger may be reversed such that the cooling

30 liquid from the housing is cooled prior to reaching the pump.

A system **52** for detecting a pressure difference across the pump **40** includes a non-obstructing flow sensor system **60**, such as a differential pressure transducer. The transducer **60** is responsive the pressure difference across the

35 pump and provides an electrical signal corresponding thereto. Specifically, the pressure transducer **60** is connected with a wall **62** of the inlet **42** by a first fluid line **64** and with a

wall **66** of the pump outlet **46** by a second fluid line **68.** The fluid lines **64** and **68** terminate at first and second diaphragms **70, 72** of the transducer, which respond to changes in the pressure in lines **64** and **66** by exhibiting volumetric changes. The changes in the diaphragms are detected by one or more volumetric detection sensors (not shown) within the pressure transducer **60** and converted to electrical voltages.

The transducer **60** does not obstruct the flow of liquid in the cooling system flow path **33**, since no liquid flows through the transducer. This avoids reduction in the flow of liquid caused by the flow measuring equipment. Additionally, in the event of a blockage or kink in one of the cooling lines **34, 36, 50**, which comprise the flow path **33**, the reduced flow downstream of the pump **40** is recognized as an increase in pressure by the downstream diaphragm **72** with no increase or a decrease on upstream diaphragm **70** and the transducer responds accordingly.

With reference now to **FIGURE 3**, power for the transducer **60** is supplied by a power source **76**, such as a DC power supply. The DC power supply is optionally tapped from the main power source of the x-ray tube and rectified. Alternatively, a separate power source, such as a set of batteries is employed. The use of batteries tends to reduce the risk of interference of electrical signals from the electrical system of the x-ray tube and thus helps to increase the accuracy of the flow measurements.

With continued reference to **FIGURE 3**, the detection system **52** further includes a processing means **80**, such as a microprocessor. The microprocessor **80** receives a signal output from the differential pressure transducer. In one embodiment, the transducer **60**, in response to a pressure difference between the inlet **42** and the outlet **46**, signals an output voltage to the microprocessor **80**. In an alternative embodiment, the transducer **60** signals first and second voltages corresponding to the input and output sensed volumetric changes. The microprocessor **80** then determines the differential voltage. In both embodiments, the microprocessor **80** converts the signal(s)

from the transducer **60** to flow rate measurements, or a
correlated function, in real time.

While a transducer **60** is a preferred non-obstructing
flow sensor system it is also contemplated that the system **60**
5   may alternatively include first and second independent flow
sensors (not shown), upstream and downstream of the pump,
respectively. Each of the flow sensors optionally includes a
diaphragm similar to diaphragms **70, 72** and an associated
volumetric sensor for detecting volumetric, pressure,
10   fluxation, or other pressure indicating changes to the
diaphragm. The two flow sensors independently send signals to
the processor **80**, which uses the signals to determine the
differential pressure and or flow rate.

There is a relationship between the liquid flow rate
15   in the cooling system **32** and the pressure difference across the
pump **40** (head pressure), which is determined experimentally and
then used to create a correlation. A typical plot of liquid
flow rate in gallons per minute (GPM) vs. the pressure
difference across a pump **40** is illustrated in **FIGURE 4** (1
20   gallon =3.785 liters). There is also a relationship between
the transducer output voltage and the head pressure. A typical
plot of head pressure vs. the transducer output is illustrated
in **FIGURE 5**. The illustrated plot was obtained using an OMEGA
PX26 differential pressure transducer which uses a 10VDC power
25   and produces a voltage signal that is proportional to the
differential pressure. By combining these two plots (**FIGS. 4**
and **5**), a correlation between liquid flow rate as a function of
transducer output is obtained, as illustrated in **FIGURE 6**.
Thus, the pressure difference detected by the transducer **60** can
30   be used to monitor the flow rate through the cooling system and
hence through the housing **30**.

With reference once more to **FIGURE 2**, the
microprocessor **80** is programmed to initiate a response if the
detected flow rate (or electrical signals corresponding
35   thereto) falls below a predetermined safe level. For example,
the microprocessor **80** also serves as a control means **81** which
signals a power switch **82**, when the flow rate falls below the

predetermined safe level. The power switch **82** responds by immediately shutting down power to the cathode **18** (or at least reducing the power to the cathode).

5   Alternatively or additionally, the processing means **80** employs an algorithm or pre-programmed look-up table to determine the energy that the x-ray tube can sustain, without risking overheating, e.g., the maximum operating time at a selected power level. In one embodiment, in the event that the determined flow rate suggests that the x-ray tube is likely to

10   overheat if it is used without allowing a sufficient cool down time, the control means **81** of microprocessor **80** provides a prompt to a user of the x-ray tube, e.g., via a video display screen **84**, to indicate that a cool down time should be allowed before the x-ray tube is used for further generation of x-rays.

15   The processor **80** calculates a suitable cool down time and optionally overrides attempts to operate the x-ray tube until the time period is over or the x-ray tube has cooled to a maximum allowable starting temperature.

In one embodiment, the processing means **80** is the

20   microprocessor associated with a control system for a radiographic device in which the x-ray tube is operated, such as a CT scanner.

While the transducer **60** is illustrated as being outside the pump **40**, it is also contemplated that the

25   transducer and optionally also the processing means **80** may be integral with the pump.

With reference now to **FIGURE 7**, an alternative embodiment of a cooling system for an x-ray tube is shown. Similar elements of the cooling system are identified by a

30   primed suffix (′) and new elements are given new numbers. One or more temperature sensors, such as resistance thermometers, or the like, detect the temperature of the cooling liquid. In the illustrated embodiment, two temperature sensors **90, 92** measure the temperature of the cooling liquid at or adjacent

35   inlet and outlet **94, 96**, respectively, of the housing **30**. For example, the sensors **90, 92** may be positioned in the outlet and return lines **34′ , 36′** , respectively. It is also contemplated

that the sensor or sensors **90, 92** could additionally or
alternatively be positioned in contact with the cooling fluid
within the housing **30**.

5   The temperature sensors **90, 92** are connected with a
processing means, such as a processor **80′**. The sensors
respond to temperature changes in the cooling liquid and send
detected temperatures or signals representative thereof to the
processor **80′**. The processor also receives signals from the
transducer **60′** in real time. The processor **80′** includes
10   algorithms, precalculated look-up tables, or other means for
converting the signals from the temperature sensors and
transducer into real time cooling fluid temperatures and
cooling liquid flow rates. The processor also includes a
thermal algorithm or other means for computing a parameter of
15   the x-ray tube, such as the x-ray tube heat storage in real
time and/or maximum energy (power-time) at which the x-ray tube
can operate without risking overheating, based on the computed
flow and temperatures and duty cycle power and time. This
information is used to control a device, such as a CT scanner,
20   which makes use of the x-ray tube **1**.

It will be appreciated that in place of receiving
inputs from temperature sensors, the processor **80** can use a
conventional algorithm or other means to predict the cooling
fluid temperature.

25   An exemplary CT scanner **100** is illustrated in **FIGURE
8**. The CT scanner radiographically examines and generates
diagnostic images of a subject disposed on a patient support
102. More specifically, a volume of interest of the subject on
the patient support **102** is moved into an examination region
30   **104**. An x-ray tube assembly **1** with an associated cooling
system **32′** is mounted on a rotating gantry **105** and projects
one or more beams of radiation through the examination region
104 to an x-ray detector **106**.

A scan controller **107** controls the scanner **100**
35   including the x-ray tube **1** to perform a selected scan protocol,
such as a single revolution multislice scan, a helical scan, a
multiple revolution examination to monitor physiological

changes or evolution, such as a cardiac scan to image selected cardiac phases, a contrast agent uptake scan, and the like, a fluoroscopic exam, a pilot scan, and the like. The scan protocols can have different durations, different x-ray tube
5   duty cycles, and different tube operating powers.

The electrical signals from the detectors **106**, along with information on the angular position of the rotating gantry, are digitized by analog-to-digital converters. The digital diagnostic data is communicated to a data memory **110**.
10   The data from the data memory **110** is reconstructed by a reconstruction processor **112**. Volumetric image representations generated by the reconstruction processor are stored in a volumetric image memory **114**. A video processor **116**, which may be the same as processor **80′**, withdraws selective portions of
15   the image memory to create slice images, projection images, surface renderings, and the like, and reformats them for display on a monitor **118** such as a video or LCD monitor.

During a scanning procedure, the processor **80′** receives temperature and pressure differential information from
20   the temperature sensors **90, 92** and pressure transducer **60′**. The processor may also receive inputs such as cycle power and number of slices to be examined in the next patient examination process from a touch screen, key pad, or other input device **120**.

25   The processor **80′** employs a thermal algorithm or means to determine a cooling condition of the x-ray tube housing **30** which corresponds to the heat stored in the x-ray tube in real time. The processor **80′** uses the cooling condition and the next scan parameters to predict whether the
30   next scanning procedure will cause the x-ray tube cooling fluid to exceed a maximum safe temperature or heat storage value and thus potentially cause damage to the x-ray tube. This allows optimization of the time between scanning procedures, steps in a scanning procedure, patient ordering, and the like. The
35   maximum safe temperature is based on information available about the performance of the particular type of x-ray tube and

includes a margin of error for ensuring safety of the x-ray tube.

A typical scanning procedure proceeds as follows:

1. The pump **40, 40′** pumps cooling fluid through the x-ray tube housing **30**.

2. The transducer **60, 60′** continuously or intermittently monitors the pressure difference of the pump and sends signals to processor.

3. The temperature sensors **90, 92** (where present) continuously or intermittently monitor cooling fluid temperature at the inlet and outlet **94, 96** of the housing **30** and send signals to processor **80′** .

4. An operator inputs selectable parameters of a scanning procedure, such as the number of slices through the processor input **120**, such as a keyboard.

5. The processor **80, 80′** inputs appropriate selectable parameters and signals from the temperature sensors and transducer **60, 60′** to an algorithm which determines the heat storage (or temperature) of the x-ray tube cooling fluid as a function of time.

6. The processor **80, 80′** and the scan controller **107** control the operation of the scanning procedure to optimize time between scans while maintaining the heat storage of the x-ray tube below a predetermined maximum level. Alternatively, the processor shuts off power to the x-ray tube until the heat storage of the x-ray tube drops to a preselected level to allow the scanning procedure to proceed without exceeding the predetermined maximum heat storage of the x-ray tube.

7. In the event that the processor detects that the maximum heat storage (or temperature) has been achieved, the processor **80, 80′** signals the power switch **82′** or scan controller **107** to switch off power immediately to the x-ray tube.

The invention has been described with reference to the preferred embodiment. Modifications and alterations will occur to others upon a reading and understanding of the preceding detailed description. It is intended that the

invention be construed as including all such modifications
and alterations insofar as they come within the scope of the
appended claims or the equivalents thereof.